# Feed Demands and Coproduct Substitution in the Biofuel Era

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## ABSTRACT

The use of traditional feedstocks for biofuel production has brought about large changes to food and agricultural systems. As livestock producers adapt to rising feed costs, the prospect of incorporating dried distiller's grain with solubles (DDGS) at higher than traditional levels becomes an important consideration. Given prices for feedstuffs and supplies of DDGS that are outside the historical data range, forward-looking analyses of the agricultural economy (even those with explicit derived demands for livestock feed) are poorly equipped to represent the farm- and sector-level tradeoffs that will emerge. The authors' results indicate that DDGS demands are more responsive to price changes in energy-oriented feeds than protein, despite the predominant historic feeding use of DDGS as a protein supplement. They extend their empirical analysis to account for the role of heterogeneous DDGS feed quality, identifying this as a critical consideration for sector-level substitution patterns. The price elasticities they report from their two-stage farm-level feed mix simulation and sector-level cost function estimation offer a robust picture of feedstuffs substitution of the type necessary for understanding the livestock component of demand response in the biofuels era. [EconLit citations: D20; C61; C13].


## 1. INTRODUCTION

Analysis of the market impacts of biofuel policies (Hertel, Tyner, & Birur, 2008; Taheripour, Hertel, Tyner, Beckman, & Birur, 2008; Tokgoz et al., 2007; Tyner, 2007; Tyner & Taheripour, 2007) have highlighted several supply and demand relationships including the role of livestock as a competitor with biofuel producers for feed grains and as a primary end-use of biofuel coproducts. However, the main coproduct from corn ethanol production, dried distiller's grain with solubles (DDGS), has frequently been incorporated into these analyses in an ad hoc fashion with little analysis of the responsiveness in feeding decisions made at the farm level. The role of livestock sector response, in particular the substitutability of biofuel coproducts in feed rations, constitutes an important gap in the literature that needs to be addressed as this area of analysis moves forward.

The use of agricultural resources in the production of animal feed, human food, and fuel creates a complex market tension that must be well understood to analyze the relative roles of international demand shifts and policy mandates for renewable fuels in driving price increases. DDGS demand by livestock producers has emerged as a critical component in understanding the effects of these impacts. Westcott (2007) uses corn to DDGS conversion factors for different livestock types to develop acreage requirements for corn when projecting agricultural market impacts resulting from the biofuel boom. More elaborate modeling frameworks have relied on somewhat ad hoc approaches to incorporate the impacts of DDGS feeding to livestock in analysis of biofuel policy impacts (Tokgoz et al., 2007; Tyner & Taheripour, 2007).

Recognition of the importance of DDGS in analyses of agricultural markets following energy policy shocks highlights both the need for and the gap in understanding DDGS substitution

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possibilities as they play out in sector-level feed demands. The simplistic treatment of DDGS feedstuffs as a perfect substitute for corn ignores the complexity of ration formulation as it is determined at the farm or feedlot level where feed demand is driven by energy and protein requirements and their relative costs in the ration (St. Pierre, Thraen, & Harvey, 1987). Historically, DDGS feed demand has served as a lower-cost (i.e., relative to soybean meal or urea) protein supplement in cattle diets (Klopfenstein, 1996). However, at recent prices the DDGS inclusion rates are being fed more for their energy value. With increased corn prices and strong growth in DDGS availability, the price responsiveness of feed demands is increasingly driven by the objective of meeting energy requirements at the lowest cost. To properly examine this issue, a model that provides for a more detailed picture of the protein and energy tradeoffs that drive farm-level feed demand in livestock sectors is needed.

The analysis conducted here provides estimates of livestock feed demand response using a combination of farm-level feed ration simulation and sector-level econometric modeling. These estimates of feed-demand substitution between energy and protein inputs with DDGS for livestock sectors in the United States offer additional evidence to improve understanding of the market impact of biofuels. The key question addressed here is the adjustment in other industries (livestock) to a now large sector that interacts with agriculture. In this work, we present both tests of standard livestock input demand hypotheses as well as price elasticities suitable for use in modeling frameworks aimed at richer development of the agricultural product and factor market impacts of changes in food and fuel demand. A primary finding is that DDGS demand tends to be more responsive to price changes in energy-oriented feeds (as opposed to protein-oriented), despite the historic feeding use of DDGS as a protein supplement in livestock diets. The role of DDGS feed quality heterogeneity is also found to be an important consideration for identifying sector-level substitution patterns. These findings underscore the value of the hybrid simulation and econometric method for developing estimates of substitution possibilities that would not be possible with historical data covering an era when DDGS represented a minor input into livestock feeding.

### 1.1. Renewable Fuels and Livestock Feed

The increase in corn-based ethanol production in the United States represents a dramatic shock to the agricultural economy. Figure 1 shows the 300% increase in ethanol output that occurred between 2001 and 2007 in response to increased ethanol additive use following methyl tertiary butyl ether (MTBE) bans, higher oil prices, and renewable fuel initiatives enacted by the federal government (Westcott, 2007). The rapid rise of agricultural prices

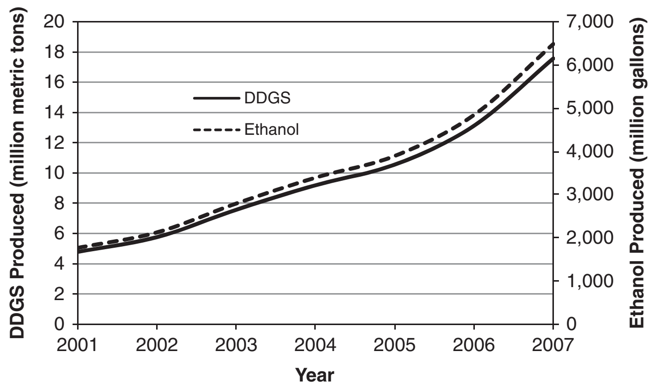


Figure 1 U.S. ethanol and dried distiller's grain with solubles (DDGS) produced, 2001–2007. (*Note*: Renewable Fuels Association and authors' calculations of U.S. Department of Agriculture's data.) We assume that one bushel of corn used for ethanol produces 17.75 pounds of DDGS. Also, we assume that three quarters of ethanol is produced in a dry mill plant.

coincident with increases in ethanol demand has generated strong interest in estimating the agricultural economy impacts. The importance of the livestock sector in determining these impacts arises from its role as a primary competitor with the ethanol industry for feed grains, while also commanding the dominant end-use share of DDGS, the primary corn ethanol coproduct.

Accompanying the rapid increase in corn-ethanol production was a similar increase in DDGS production (Fig. 1). This surge in DDGS production has occurred at a time of rapid cost increases for livestock feedstuffs for corn and soybean meal. Because feed costs are generally the largest share of livestock production costs, and with fuel mandates driving up both DDGS supplies and cost of feed grain inputs, the potential for adjusting livestock feed rations to include more DDGS inputs has generated significant interest. Clemens and Babcock (2008) review studies of livestock feeding possibilities and conclude that the livestock sector has significant potential to increase DDGS use in response to the growing supply if price, quality, and availability issues become more favorable. A primary issue raised by these authors is the nutritional constraints that limit DDGS inclusion in diets, and the potential for ethanol sector adjustments to produce a feed coproduct that extends the nutritional limits on inclusion. Other research has found that livestock response (estimated from a number of feeding trials) to excessive (relative to traditional recommendations) DDGS use in rations may not be a limiting economic factor if DDGS prices fall low enough relative to those for grains (Jones, Tonsor, Black, & Rust, 2007).

## 2. PREVIOUS WORK ON LIVESTOCK FEED SUBSTITUTION

Previous analyses integrating detailed livestock ration formulation and economic substitution possibilities focused primarily on the compound feeds sector of the European Union (e.g., Mergos & Yotopoulos, 1988; Rude & Meilke, 2000; Surry, 1990). Analysis of the EU Common Agricultural Policy (CAP) reforms over the last two decades helped focus attention on relative grain prices and feedstuffs demand for understanding equilibrium impacts. In one of the more recent analyses, Rude and Meilke (2000) estimate livestock-feed demand substitution possibilities to examine the effect of reduced intervention prices for cereals in the European Union (EU), finding only modest impacts on feed demand due to limited cross price effects.

Feed recommendations are traditionally based on least cost ration linear programming (LP) models to guide mixing decisions. McKinizie, Paarlberg, and Huerta (1986) exploit information from representative ration models to summarize the substitution possibilities between feed ingredients in the Netherlands. Their two-stage approach consists of econometrically estimating feed technology using synthetic data on prices and demands as simulated by an LP ration model. The appeal of the McKinizie and colleagues' (1986) approach for estimating feed demand rests on the minimal demands for historical data and the ability to robustly characterize substitution possibilities over a broad domain of the price space. In another use of this two-stage approach; Surry (1990) uses a spatial price equilibrium model of the European Community grain markets to estimate derived demands for feed ingredients that have been adopted by modelers (e.g., Keeney & Hertel, 2005; Rae & Strutt, 2005), but this information is of limited value for inclusion of biofuel coproducts.

Linear programming models have received sustained use for analyzing changes in feed demand under different price forecasts and for new feed ingredients. Recent LP ration studies of DDGS use in the U.S. livestock sector have focused on how feed demands are impacted by transportation costs, manure management (e.g., phosphorous content), and emerging technology improving the feed quality of DDGS (Bista, Hubbs, Richert, Tyner, & Preckel, 2008; Jones et al., 2007). The role of DDGS feed quality and consistency has emerged as a key point in the analysis of livestock feeding representing a new management focus for ethanol producers. Variable nutrient quality across DDGS sources has been identified as an important factor limiting adoption by livestock producers (Fabiosa, 2008). Other analysis of the supply side of DDGS production clearly points to the role of joint production management of ethanol for fuel and the animal feed coproducts as a critical determinant of sustained profitability in the ethanol production industry (Clemens & Babcock, 2008).

## 3. DISTRIBUTION INPUTS AND PROCESS MODEL

Ideally, historical data would be used to estimate livestock-feed response; however, data on historical DDGS use and the corresponding prices are of limited information value considering the economic environment in which equilibrium ethanol production and DDGS feed demand will eventually be determined. Thus, the pseudo-data approach of McKinizie et al. (1986) is utilized in the current analysis. This allows simulation analysis of livestock producer behavior when considering a wide range of inputs and possible price combinations.

### 3.1. Overview of the Pseudo-Data Approach

Klein (1953) coined the term pseudo-data to describe observations generated by iteratively solving an economic model with respect to changes in some exogenous parameter. Griffen (1977, 1978) demonstrated this approach using oil refinery process models. With respect to agriculture, Hertel and McKinzie (1986) and Preckel and Hertel (1988) use pseudo-data derived from the Center for Agricultural and Rural Development (CARD) agricultural model to estimate summary function supply and demand response to new farm and conservation policies proposed in the 1980s.

The pseudo-data approach has received a fair amount of criticism in terms of replacing an econometric approach using observed data. In a review of estimated price elasticities for EU livestock, Peeters and Surry (1997) conclude that the pseudo-data approach leads to larger elasticities than those produced by economic analysis using observed time-series data. McKinizie et al. (1986) compared the results from their LP-pseudo-data approach to actual rations, and conclude that their approach matches the actual rations well.

The approach as outlined in McKinizie et al. (1986) requires development of a suitable least-cost ration simulation model and repeated solutions over varying prices to determine changes in demand quantities. In the first stage, in which data on prices and corresponding optimal quantities are identified, the authors highlight the importance of price distribution to ensure that appropriate LP basis changes are considered under expected price ratios of feedstuffs. In particular, numerous basis changes are needed to mitigate possible bias in the econometric estimation because the error terms in the estimation are a direct result of the chosen price variation.

### 3.2. Relative Prices and Their Historical Distribution

Table 1 lists the feed ingredients incorporated into the least cost ration model, including information on (monthly) average prices and variability during the 2001–2008 period. The last column provides a classification for non-DDGS feedstuffs as either an energy or protein input based on their primary diet contribution (National Resource Council, 2000). Results in Table 1 show that the DDGS price was higher (per pound) than that of corn, but with lower variability over the 8-year period. Similarly, the historic price distributions indicate that energy inputs were priced on a per pound basis lower than protein feeds, but that processed protein feed prices were considerably less volatile over that same period.

The information on historical prices given in Table 1 is used to develop a distribution for each feed input price. Random draws from this distribution are then used to find corresponding feed demands from the least-cost feed ration model. Based on strong correlation between feedstuff prices over the historical period (e.g., all coefficients greater than .68 with respect to corn) feed input prices are modeled with a joint normal distribution. Price correlations are strongest between feed inputs within their own classification (i.e., energy or protein) and corn and DDGS price correlation is high (.81).[1] Figure 2 provides a look at the resulting price distribution for DDGS, with the dotted line indicating the mean price.

[1]Correlations among all feed inputs are available upon request.

TABLE 1. Descriptive Statistics and Classification for Feed Inputs

| Feed input | Average price traditional units | Average price (per/lbs) | Range | Standard deviation | CV | Classification |
|---|---|---|---|---|---|---|
| DDGS | 95.54 ($/ton) | 0.0478 | [.023,.083] | 0.0116 | 0.2438 | DDGS |
| Alfalfa Hay | 106.81 ($/ton) | 0.0533 | [.042,.064] | 0.0073 | 0.1365 | Energy |
| Prarie Hay | 85.16 ($/ton) | 0.0428 | [.033,.064] | 0.0088 | 0.2050 | Energy |
| Corn | 2.56 ($/bushel) | 0.0457 | [.032,.096] | 0.0137 | 0.2999 | Energy |
| Hominy | 73.38 ($/ton) | 0.0367 | [.077,.173] | 0.0122 | 0.3312 | Energy |
| Corn Silage | 22.05 ($/ton) | 0.0102 | [.007,.021] | 0.0031 | 0.2999 | Energy |
| Wheat Middlings | 68.39 ($/ton) | 0.0342 | [.023,.077] | 0.0137 | 0.3994 | Energy |
| Oats | 2.31($/bushel) | 0.0721 | [.011,.085] | 0.0155 | 0.2153 | Energy |
| Barley | 2.90 ($/bushel) | 0.0603 | [.065,.113] | 0.0226 | 0.3740 | Energy |
| Wheat | 3.85 ($/bushel) | 0.0641 | [.054,. 146] | 0.0208 | 0.3252 | Energy |
| Sorghum | 4.87 ($/bushel) | 0.0864 | [.048,.119] | 0.0239 | 0.2770 | Energy |
| Soybean Meal | 200.77 ($/ton) | 0.1004 | [.041,.153] | 0.0236 | 0.2349 | Protein |
| Canola Meal | 156.04 ($/ton) | 0.0780 | [.103,.281] | 0.0114 | 0.1457 | Protein |
| Cottonseed Meal | 151.81 ($/ton) | 0.0759 | [.060,.113] | 0.0161 | 0.2125 | Protein |
| Corn Gluten Meal | 296.74 ($/ton) | 0.1484 | [.044,.146] | 0.0406 | 0.2739 | Protein |
| Alfalfa Meal | 156.37 ($/ton) | 0.0782 | [.064,.171] | 0.0151 | 0.1936 | Protein |

*Source*: Monthly, Crop Year 2001–2007 Prices. Agriculture Marketing Service, National Agricultural Statistical Service, U.S. Department of Agriculture (2007).

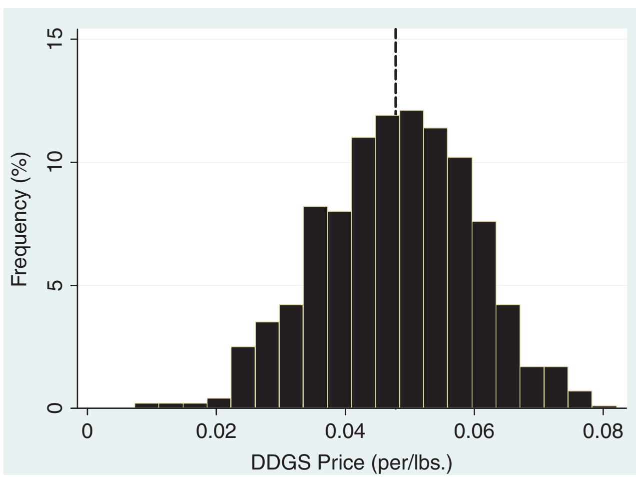


Figure 2 Distribution of generated dried distiller's grain with solubles price.

From the choice of a joint normal distribution and the information in Table 1, DDGS and energy feed inputs will be priced on average lower than protein feed inputs in the pseudo-data sample, and DDGS prices will tend to follow more closely those for corn due to the high correlation. With the reliability of the estimates drawn from pseudo-data being dependent on generating many basis changes (McKinzie et al., 1986), 1,000 price combinations are drawn from the distribution to ensure coverage of the price space (and the concomitant shifts in the LP basis).

### 3.3. Least-Cost Ration Models

The least cost ration model utilized here is a standard LP ration model where one pound of feed is fed at minimum cost, given prices and nutritional constraints. Equation 1 offers the general form of the model with $p_i$ as the price of the $i$th feed input, $x_i$ the demand for that input, $a_{ji}$ as the content of nutrient $j$ in feed $i$ and $UL$ and $LL$ representing lower and upper feeding bounds determined by nutrient requirements and limits. Finally, the last two constraints ensure nonnegative use of inputs, and the summation of inputs consumed to equal one pound.

$$Minimize \sum_i p_i x_i$$

$$\begin{aligned} \text{subject to :} \quad & \sum_i a_{ji} x_i \geq LL_j \\ & \sum_i a_{ji} x_i \leq UL_j \\ & x_i \geq 0 \\ & \sum_i x_i = 1 \end{aligned} \tag{1}$$

The relative prices and the nutritional contributions will determine what feeds are used for a given animal type. A version of the model in Equation 1 is used for multiple stages of cattle (ruminant) and swine (nonruminant) feeding. Nutritional contributions for feed inputs are taken from the National Resource Council (1996, 2000). The nutritional requirements differ in the models across animal types and stages of growth. The weight classes are relatively straightforward,[2] and are given on a per pound basis for swine in Table 2. Swine raised for slaughter, and reproduction (the last two columns are needed nutrients for sows) are considered. From Table 2 notice that the minimum amount of crude protein needed decreases as weight increases, as does the level of other nutrients. The maximum amount of crude fat and crude fiber that can be fed is the same across weight classes. The last six rows are essential amino acids, with lysine being the most limiting amino acid in swine diets leading to a specification in which a fixed amount of lysine must be fed with other nutritional requirements driven by this level (Augenstein, Johnston, Shurson, Hawton, & Pettigrew, 1997).

Table 3 provides similar information for beef cattle, based on information from the National Resource Council (2000). For these models, three types of roughage (alfalfa hay, prairie hay, and corn silage) are included. Beef cattle requirements differ by sex as well as stage of production with three weight classes for slaughter steers 500, 700, and 1,100 pounds. For females, unbred heifers (500 lb) are considered as well as the requirements in development for a 1,200- and 1,400-lb mature cow. For each of these mature weights there are three growth stages: newly bred, lactating, and gestating, designed to capture major changes in nutritional requirements.

For beef cattle there are only four nutritional requirements that differ across weight class and gender: net energy, calcium, phosphorus, and protein intake. Other nutritional requirements and limits are included in the beef diets, but do not differ across growth stages, hence only minimum and maximum requirements are provided. Examining Table 3, steers net energy requirements increase as weight increases; however, protein intake and calcium minimum requirements decrease. This will have important implications for the LP models, as steers switch from a more protein intensive diet, to an energy-based diet as weight increases. For females, the lactating period is the most demanding in terms of nutritional requirements.

### 3.4. DDGS Quality

Nutrient composition of DDGS is known to differ across plants, as primary feedstock (e.g., corn or sorghum) and production techniques vary. This variability and how it presents in the

[2]Weight classes under 22 lbs. are not considered, as these types are not raised entirely on feed. Also, boars are not considered, as their reported numbers are small.

TABLE 2. Nutritional Requirements for Swine

| | 22–44 lbs. | | 44–110 lbs. | | 110–176 lbs. | | 176–256 lbs. | | Gestating Sow | | Lactating Sow | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nutrient requirements | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max |
| Metabolize Energy (kcal) | 1,500 | | 1,500 | | 1,500 | | 1,500 | | 1,480 | | 1,550 | |
| Crude Protein (%) | 0.20 | | 0.18 | | 0.15 | | 0.14 | | 0.12 | | 0.16 | |
| Calcium (per/lb) | 0.009 | 0.010 | 0.007 | 0.008 | 0.007 | 0.008 | 0.006 | 0.007 | 0.008 | 0.010 | 0.008 | 0.010 |
| Phosphorous (per/lb) | | 0.009 | | 0.007 | | 0.007 | | 0.006 | | 0.008 | | 0.008 |
| Available Phosphorus (per/lb) | | 0.005 | 0.003 | | 0.002 | | 0.002 | | 0.004 | 0.005 | 0.004 | 0.005 |
| Crude Fiber (per/lb) | | 0.035 | | 0.035 | | 0.035 | | 0.035 | | 0.035 | | 0.035 |
| Crude Fat (per/lb) | | 0.070 | | 0.070 | | 0.070 | | 0.070 | | 0.070 | | 0.070 |
| Methionine (per/lb) | 0.006 | 0.007 | 0.006 | 0.007 | 0.005 | 0.006 | 0.004 | 0.005 | 0.003 | | 0.006 | |
| Threonine (per/lb) | 0.006 | 0.007 | 0.006 | 0.007 | 0.005 | 0.006 | 0.005 | 0.006 | 0.003 | | 0.006 | |
| Trytophan (per/lb) | 0.002 | 0.003 | 0.002 | 0.003 | 0.001 | 0.002 | 0.001 | 0.002 | 0.001 | | 0.001 | |
| Lysine (per/lb) | 0.010 | 0.010 | 0.010 | 0.010 | 0.009 | 0.009 | 0.007 | 0.007 | 0.004 | 0.004 | 0.008 | 0.008 |
| Isoleucine (per/lb) | 0.006 | | 0.005 | | 0.005 | | 0.004 | | 0.002 | | 0.005 | |
| Valine (per/lb) | 0.007 | | 0.006 | | 0.006 | | 0.005 | | 0.003 | | 0.005 | |

TABLE 3. Nutritional Requirements for Beef Cattle

| | | | Steer | | | Heifer | 1,200 lb Cow | | | 1,400 lb Cow | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 500 lb | 700 lb | 1,100 lb | 500 lb | Newly Bred | Lactating | Gestating | Newly Bred | Lactating | Gestating |
| | Min | Max | Min | Min | Min | Min | Min | Min | Min | Min | Min | Min |
| Nenergy (per lb) | | | 0.607 | 0.68 | 0.714 | 0.55 | 0.525 | 0.627 | 0.536 | 0.539 | 0.665 | 0.529 |
| Calcium (per lb) | | 0.2 | 0.0055 | 0.0052 | 0.0030 | 0.0030 | 0.0024 | 0.0036 | 0.0026 | 0.0023 | 0.0035 | 0.0026 |
| Phosphorus (per lb) | | 0.1 | 0.0022 | 0.0027 | 0.0016 | 0.0016 | 0.0019 | 0.0026 | 0.0021 | 0.0018 | 0.0026 | 0.0021 |
| Protein_Intake (per lb) | | | 0.1236 | 0.1200 | 0.0890 | 0.1120 | 0.0860 | 0.1150 | 0.0690 | 0.0820 | 0.1100 | 0.0760 |
| Magnesium (per lb) | 0.001 | 0.004 | | | | | | | | | | |
| Potassium | 0.006 | 0.030 | | | | | | | | | | |
| Sodium | 0.0006 | | | | | | | | | | | |
| Sulfur | 0.0015 | | | | | | | | | | | |
| Copper (mg/lb) | 4.550 | 45.455 | | | | | | | | | | |
| Iron (mg/lb) | 22.727 | 454.545 | | | | | | | | | | |
| Manganese (mg/lb) | 9.091 | 454.545 | | | | | | | | | | |
| Selenium (mg/lb) | 0.045 | 0.909 | | | | | | | | | | |
| Zinc (mg/lb) | 13.636 | 227.273 | | | | | | | | | | |

TABLE 4. Descriptive Statistics of 40 DDGS Producing Plants

| Nutrient | Average | Range | Standard deviation | CV |
|---|---|---|---|---|
| Metabolize Energy (kcal) | 1,732 | [1,589,1,836] | 58.01 | 0.03 |
| Crude Protein (per/lb) | 0.308 | [.273,.339] | 0.015 | 0.05 |
| Calcium (per/lb) | 0.052 | [0.02,.12] | 0.030 | 0.58 |
| Phosphorous (per/lb) | 0.781 | [0.42,1.06] | 0.129 | 0.17 |
| Crude Fiber (per/lb) | 7.44 | [5.37,10.58] | 1.194 | 0.16 |
| Crude Fat (per/lb) | 11.10 | [3.52,13.46] | 1.693 | 0.15 |
| Methionine (per/lb) | 0.630 | [0.54,.76] | 0.056 | 0.09 |
| Threonine (per/lb) | 1.136 | [1.01,1.25] | 0.058 | 0.05 |
| Trytophan (per/lb) | 0.239 | [0.18,.34] | 0.032 | 0.13 |
| Lysine (per/lb) | 0.944 | [0.61,1.17] | 0.124 | 0.13 |
| Isoleucine (per/lb) | 1.177 | [1.01,1.31] | 0.076 | 0.06 |
| Valine (per/lb) | 1.570 | [1.31,1.72] | 0.108 | 0.07 |

*Note*. DDGS = Dried distiller's grain with solubles.
*Source*: University of Minnesota (2008).

aggregate DDGS supply is a critical component for reconciling farm- and sector-level substitution possibilities between DDGS and other feed inputs. The University of Minnesota (2008) provides analysis of the nutritional content of DDGS across 40 sample plants.[3] The descriptive statistics for these are presented in Table 4, with respect to swine nutrient demands. In general, Table 4 indicates that the DDGS energy content lower bound is high relative to corn and that the protein content upper bound is low relative to soybean meal.

Notable in Table 4 is the high variability in calcium content across DDGS production at different plants. This will have important implications for the simulation results because protein feeds such as soybean meal and corn gluten meal are high in calcium content. In particular, meeting the upper limit on calcium in swine diets will be an important determinant in feed demand adjustment with respect to protein, energy, and DDGS.

To incorporate the variation of the nutrient composition of DDGS, the vector of DDGS nutritional contributions is specified as a stochastic element in the nutrient composition matrix of the linear program. Using the average variability and means from the data in Table 4, a normal distribution is generated (independent of the price distribution) of DDGS feed qualities with each solve of the model randomly drawing from this distribution to complete the matrix with a unique DDGS vector. The resulting distribution for metabolized energy is given in Figure 3.

## 4. DEMAND DATA AND ESTIMATION

This section reports the simulation model data examining the quantity price relationships as by the least cost feed ration linear program. Then the approach to estimating livestock sector response is detailed.

### 4.1. LP-Generated Data

Repeated solutions of the least cost LP provides 1,000 observations for each livestock type and growth stage previously discussed. The LP results are only presented for swine; however, the same results/discussion applies to beef.[4] Figure 4A shows a plot of the inverse quantity demanded of DDGS for the DDGS/energy price ratio with respect to invariant average

[3]Note that most of the plants (38) are ethanol producing; however, DDGS are produced by other sources.

[4]Wheat middlings from beef cattle diets are excluded because they tended to enter the diets in great amounts (e.g., more than 50%), which is inconsistent with the limited supplies expected for this feed component.

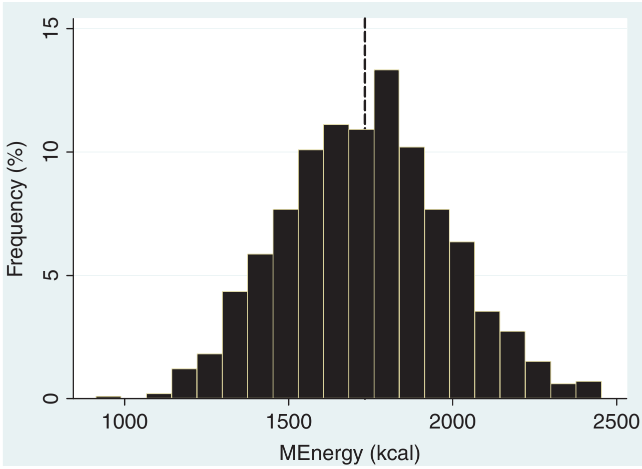


Figure 3 Metabolize energy distribution for dried distiller's grain with solubles stochastic programming.

DDGS quality. Figure 4B offers the same information when DDGS quality is allowed to vary. Both indicate a downward sloping relationship with that of constant quality DDGS being more responsive to price. However, the limited number of unique demands evident in Figure 4A indicates how restrictive the LP formulation is for measuring sector-level response. In contrast, Figure 4B shows a large number of DDGS shares in feed demand with the variation in DDGS feed quality adding a flavor of cross-sectional variation to the estimation. With the focus on DDGS demand response and detailed data on differences by plants in DDGS feed quality, generating demands from the LP model in this fashion is clearly preferable.

DDGS historical use as a livestock feed has also been as a protein supplement. Thus in Figure 5, DDGS quantity demanded from the LP simulation are plotted versus the DDGS/protein price ratio (varying DDGS quality). Comparing these results to those in Figure 4B, the conclusion is that DDGS quantity demanded responds more to a decrease in relative energy price, than to protein price for the same class because the slope is steeper than that for protein price.

### 4.2. Estimating Framework

After repeated solution of the LP models over the distribution of prices, the next step is to utilize the prices and derived quantities demanded to approximate a representative sector cost function. To move from the farm-level simulation model to a sector-level model appropriate for econometric modeling, the appropriate aggregation scheme must be determined. The goal of this article is to provide evidence and conclusions about livestock feed demand response with respect to DDGS; therefore, results from the simulation model are aggregated into three input categories, as is typically done in livestock-feed estimation (e.g., Mergos & Yotopoulos, 1988; Surry, 1990; Surry & Moschini, 1984). The cost function for livestock producers is then:

$$C_F = C(P_{DDGS}, P_{Energy}, P_{Protein}) \tag{2}$$

where $C_F$ is the cost of feed, and $P_i$(DDGS, energy, and protein) is the price of feed components. To aggregate feed inputs from the LP models to the level of aggregation given in Equation 2, a Divisia index of prices and quantities is constructed, appropriate for demand estimation.

Following guidance from previous work estimating summary functions from process models (Griffen, 1978; McKinzie et al., 1986; Mergos & Yotopoulos, 1988) we estimate the

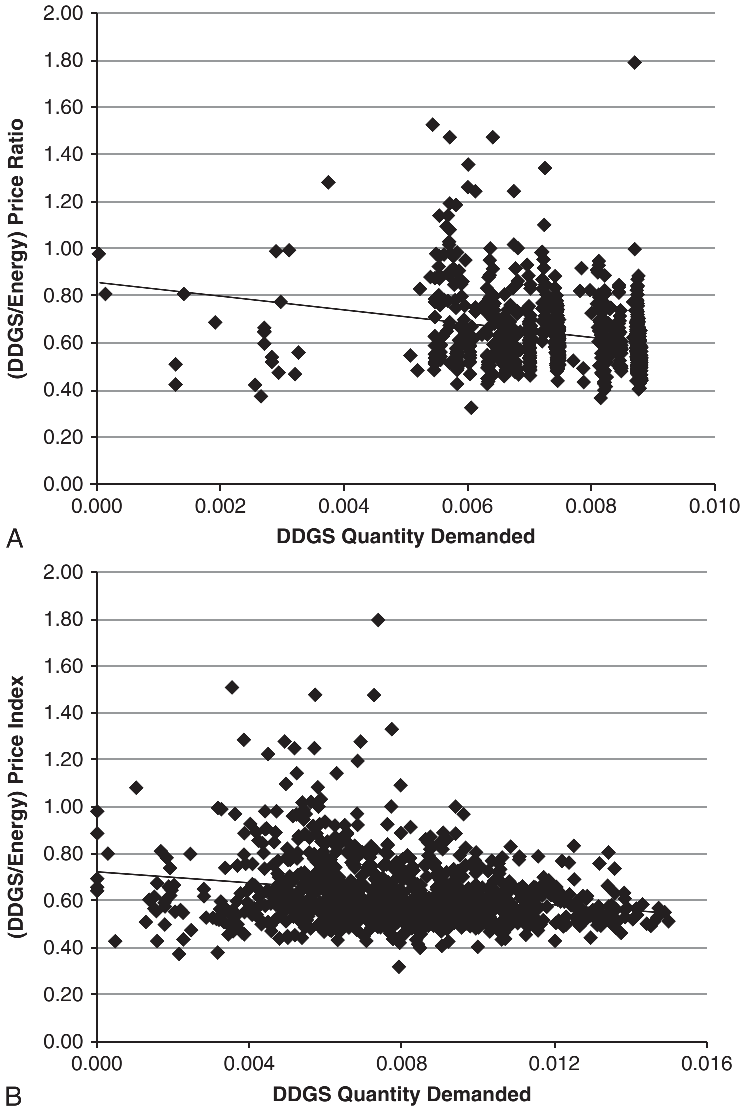


Figure 4 (**A**) DDGS quantity demanded at dried distiller's grain with solubles (DDGS)/energy price ratio for swine, average DDGS quality. (**B**) DDGS quantity demanded at DDGS/energy price ratio for swine, varying DDGS quality.

translog cost function as specified in Equation 3:

$$\ln C = \alpha_0 + \sum_{i}^{3} \beta_i \ln P_i + \frac{1}{2}\sum_{i}^{3}\sum_{j}^{3} \varphi_{ij} \ln P_i \ln P_j \tag{3}$$

with the typical restrictions:

$$\sum_{i}^{3} \beta_i = 1,$$

$$\sum_{i}^{3} \varphi_{ij} = 0 = \sum_{j}^{3} \varphi_{ji}$$

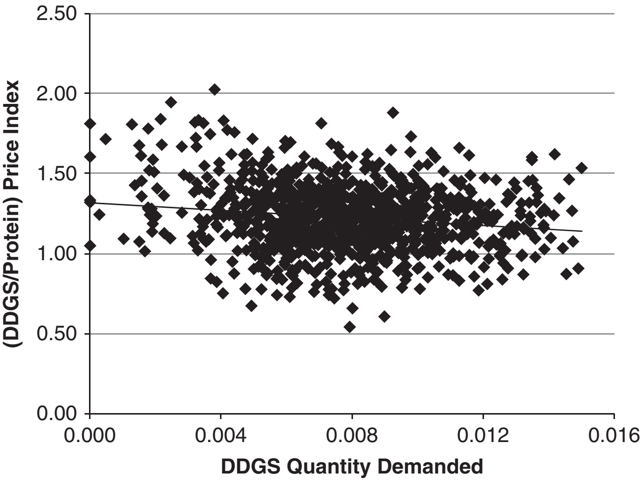


Figure 5 Dried distiller's grain with solubles (DDGS) quantity demanded at DDGS/protein price ratio for swine, varying DDGS quality.

where $C$ is total cost, $P_i$ is the cost of input $i$, and the two restrictions ensure the cost function is homogenous of degree 1.

Shephard's lemma provides that differentiating Equation 3 with respect to each input price yields the demand equations in share form are as in Equation 4:

$$S_i = \beta_1 + \sum_{j}^{3} \phi_{ij} \ln P_i \tag{4}$$

with the same parameter restrictions as given in Equation 3. Estimating the system of share equations using Seemingly Unrelated Regression (SUR) gives the estimated parameters for $\phi_{ij}$, which are used to calculate own- and cross-price elasticities as show in Equation 5:

$$\begin{aligned} \varepsilon_{ii} &= \frac{\phi_{ii}}{S_i} + S_i - 1, \\ \varepsilon_{ij} &= \frac{\phi_{ii}}{S_i} + S_j \end{aligned} \tag{5}$$

## 5. RESULTS

### 5.1. Estimates

Table 5 presents the full set of parameter estimates of the cost function for swine,[5] for both constant DDGS and varying DDGS quality. Both models have a high $R^2$ indicating that the models are well specified, and all coefficients are statistically significant for the first model. The coefficient for the variable $\phi_{12}$ ($\ln P_1 * \ln P_2$) is not statistically significant at the .05 level, for heterogeneous DDGS quality.

Turning to the estimation results for beef cattle (Table 6), results indicate that the $R^2$ is still high for both models. The results of the cost function estimation convey how well the models perform statistically; however, the parameter estimates have little economic meaning. Rather, they best serve as the basis for calculation of elasticities of substitution (Binswanger, 1974).

[5]Note from Equation 3, $i$ = DDGS, energy, and protein.

TABLE 5. Results of Estimation for Translog Cost Function, Swine

| Constant DDGS quality | | | Varying DDGS quality | |
|---|---|---|---|---|
| Variable | Coefficient | Standard error | Coefficient | Standard error |
| $\alpha_0$ | −3.138 | 0.001 | −3.129 | 0.001 |
| $\beta_1$ | 0.161 | 0.002 | 0.153 | 0.004 |
| $\beta_2$ | 0.388 | 0.002 | 0.387 | 0.004 |
| $\beta_3$ | 0.451 | 0.002 | 0.460 | 0.003 |
| $\varphi_{11}$ | 0.037 | 0.006 | 0.026 | 0.014 |
| $\varphi_{12}$ | −0.021 | 0.003 | 0.001 | 0.008 |
| $\varphi_{13}$ | −0.016 | 0.004 | −0.027 | 0.009 |
| $\varphi_{22}$ | 0.148 | 0.003 | 0.127 | 0.007 |
| $\varphi_{23}$ | −0.127 | 0.003 | −0.128 | 0.005 |
| $\varphi_{33}$ | 0.143 | 0.005 | 0.155 | 0.007 |
| | $R$-Squared = .995 | | $R$-Squared = .991 | |

*Note*. DDGS = Dried distiller's grain with solubles.

TABLE 6. Results of Estimation for Translog Cost Function, Beef Cattle

| Constant DDGS quality | | | Varying DDGS quality | |
|---|---|---|---|---|
| Variable | Coefficient | Standard error | Coefficient | Standard error |
| $\alpha_0$ | −3.218 | 0.002 | −3.066 | 0.003 |
| $\beta_1$ | 0.092 | 0.002 | 0.066 | 0.002 |
| $\beta_2$ | 0.458 | 0.003 | 0.275 | 0.002 |
| $\beta_3$ | 0.450 | 0.004 | 0.659 | 0.003 |
| $\varphi_{11}$ | 0.023 | 0.009 | −0.028 | 0.007 |
| $\varphi_{12}$ | −0.045 | 0.004 | 0.021 | 0.003 |
| $\varphi_{13}$ | 0.022 | 0.008 | 0.007 | 0.006 |
| $\varphi_{22}$ | 0.007 | 0.008 | 0.134 | 0.004 |
| $\varphi_{23}$ | 0.037 | 0.008 | −0.155 | 0.004 |
| $\varphi_{33}$ | −0.059 | 0.011 | 0.148 | 0.008 |
| | $R$-Squared = .835 | | $R$-Squared = .770 | |

*Note*. DDGS = Dried distiller's grain with solubles.

TABLE 7. Average Feed Cost Shares, Constant and Varying DDGS Quality, Swine, and Beef

| | Swine | | Beef | |
|---|---|---|---|---|
| | Constant | Varying | Constant | Varying |
| DDGS | 0.15 | 0.16 | 0.10 | 0.06 |
| Energy | 0.48 | 0.47 | 0.41 | 0.27 |
| Protein | 0.37 | 0.37 | 0.49 | 0.67 |

*Note*. DDGS = Dried distiller's grain with solubles.

Estimated cost shares for swine indicate that energy makes up the largest share for both fixed and varying quality models, followed by protein, and then DDGS (Table 7). These results are relatively constant across the two models. However, the cost shares for beef indicate substantial differences between the two models. The average cost share for DDGS is

TABLE 8. Demand Elasticities, Constant and Varying DDGS Quality, Swine (Standard Errors in Parentheses)

| | Constant DDGS quality price | | | Varying DDGS quality price | | |
|---|---|---|---|---|---|---|
| Demand | DDGS | Energy | Protein | DDGS | Energy | Protein |
| DDGS | −0.589 | 0.093 | 0.096 | −0.653 | 0.121 | 0.053 |
| | (0.010) | (0.010) | (0.008) | (0.023) | (0.022) | (0.019) |
| Energy | 0.320 | −0.213 | 0.146 | 0.483 | −0.257 | 0.159 |
| | (0.015) | (0.002) | (0.007) | (0.006) | (0.002) | (0.018) |
| Protein | 0.269 | 0.120 | −0.242 | 0.170 | 0.135 | −0.212 |
| | (0.006) | (0.011) | (0.001) | (0.028) | (0.021) | (0.001) |

*Note*. DDGS = Dried distiller's grain with solubles.

reduced from .10 to .06 when quality varies. The largest cost share for both models is attributable to protein; however, the model with varying DDGS quality has a much larger protein share (.67) than the model with constant DDGS quality (.49).

### 5.2. Sector-Level Elasticities

Demand elasticities are estimated according to Equation 4.[6] Elasticity results differ across the two models indicating that the use and quality of DDGS matters greatly. Focusing first on swine, Table 8 indicates that the own-price elasticity is more elastic for DDGS than for energy or protein, for both models. Comparisons across the two models reveal that DDGS own-price elasticity has become more responsive with varying quality; and that the cross-price elasticity between DDGS and energy has become more elastic, at the expense of DDGS and protein.

Elasticity estimates are often presented without any accompanying information on the reliability of those estimates, such as statistical properties. Using the bootstrapping method, 500 samples are drawn with replacement to calculate the standard error of the elasticity estimates. These results are given in Table 8 for swine for the two cases. Examining the statistical significance of the elasticity estimates, Table 8 indicates that all are statistically significant from zero at the .01 level. The calculation of standard errors for swine does not present a wealth of new information; rather they indicate that the elasticity estimates are statistically significant.

Results of the demand elasticities for beef cattle are given in Table 9. These results highlight the importance of considering heterogeneous DDGS quality. By varying quality, the own-price elasticity of DDGS has become much more responsive than the estimate for the other two inputs. Examining the cross-price elasticities, another major difference between the two models is revealed. With constant DDGS quality, the cross-price elasticity between DDGS and energy and protein is small; however, when DDGS quality varies, the cross-price response becomes more elastic.

Table 9 presents the standard error of the elasticity estimates for beef. For constant quality the most interesting result is that all elasticity estimates are not statistically different from zero. When heterogeneous DDGS is considered, different results arise. Here the own-price elasticity for DDGS is statistically significant (at the .05 level). However, the own-price elasticity for energy and protein are not, which is likely due to the high level of aggregation within the sectors (i.e., most changes take place between corn and barley, for example). The

[6]Local concavity at the sample means is first tested by checking if the Hessian matrix is negative semidefinite. Indeed, the calculation of the Hessian indicates that local concavity holds at the sample means for all models. Examining the cost shares for swine and beef (Table 7), monotonicity in input prices holds, as all average cost shares are nonnegative.

TABLE 9. Demand Elasticities, Constant and Varying DDGS Quality, Beef (Standard Errors in Parentheses)

| | Constant DDGS quality price | | | Varying DDGS quality price | | |
|---|---|---|---|---|---|---|
| Demand | DDGS | Energy | Protein | DDGS | Energy | Protein |
| DDGS | −0.977 | −0.021 | 0.059 | −1.900 | 0.142 | 0.045 |
| | (4.748) | (1.483) | (0.044) | (0.725) | (0.009) | (0.014) |
| Energy | −0.013 | −0.916 | 0.143 | 0.914 | −0.119 | 0.001 |
| | (9.164) | (1.033) | (0.205) | (0.519) | (0.096) | (0.025) |
| Protein | 1.100 | 0.937 | −0.202 | 0.984 | −0.023 | −0.046 |
| | (4.490) | (1.665) | (0.248) | (0.209) | (0.105) | (0.038) |

*Note*. DDGS = Dried distiller's grain with solubles.

results indicate that all cross-price elasticities with respect to a change in DDGS price are now statistically significant. Furthermore, the cross-price elasticities with respect to a change in the demand for DDGS are now statistically significant.

The difference across the two models for the two sectors is essentially due to differences in nutritional constraints. In the beef models, calcium minimum constraints were often bounded. DDGS have much more calcium than energy inputs; and, when constant DDGS quality is used they enter into every model predominately as a source of calcium. In fact, often the quantity of DDGS would reach the 40% feeding maximum specified before. DDGS would then compete with other calcium-rich inputs (i.e., protein) more on a per-price basis than with energy-based inputs. When DDGS quality varies, the amount of calcium provided varies, and DDGS and the other inputs become competitive.

### 5.3. Aggregate Livestock Elasticity

The elasticities provided above are sector-specific; however, we would like to provide a possible aggregate livestock DDGS elasticity. One popular method suggested in the literature (see McKinizie et al., 1986, p. 38) makes use of historical ration quantities by sector to aggregate to the industry-level. However, this data is not available (specifically for DDGS). Therefore, we provide an "indirect" approach to calculating this elasticity.

To calculate the overall DDGS price elasticity, we make use of the computable general equilibrium (CGE) model "GTAP."[7] We incorporate the estimated elasticities from the varying DDGS models into the livestock/feed decision nest in the CGE model. These elasticities are the cross-price elasticities for DDGS/energy, DDGS/protein, and energy/protein, and are in the form of Allen-Partial elasticities (this is the form suitable for the model). We then run a small biofuels shock, and take the percentage change in quantity of DDGS divided by the percentage change in DDGS price as the aggregate-livestock DDGS own-price elasticity, i.e.,:

$$\varepsilon_{DDGS} = \frac{\%\Delta Q_{DDGS}}{\%\Delta P_{DDGS}} \tag{6}$$

The result is an elasticity estimate of −2.66, i.e., a 1% increase in the price of DDGS will lead to a 2.66% decrease in the quantity demanded of DDGS.

[7]Specifically, we utilize the version known as GTAP-BIO, see Hertel et al. (2008). Note that the elasticity calculation in this form is a general equilibrium elasticity; hence, the cross-demand elasticities could possibly influence this calculation.

## 6. DISCUSSION

It is clear that the rapid increase in biofuels production is bringing dramatic changes to food and agricultural systems. Increased corn usage for biofuels in the United States has meant that less corn is available for feed at much higher prices. The price of the other main commodity used for feed, soybeans, has also increased as acreage is shifted to corn production. At the same time, ethanol production from corn produces a feed coproduct (DDGS) that can be utilized in varying degrees in feed rations. Although DDGS have the potential to have a large impact on the derived demand for feedstuffs, and hence the structure of agricultural production, historical price relationships will offer only limited insight into future market changes given the increasing presence of biofuels as a source of grain demand and supplier of feed inputs. The role of livestock sector response, in particular the substitutability of biofuels coproducts in feed rations, represents an important gap in the literature that this article has addressed to help move this analysis forward.

This article offers some of the first econometric evidence on feed demand substitution between energy and protein inputs with DDGS for the ruminant and nonruminant livestock sectors in the United States. The role of DDGS feed quality heterogeneity is shown to be an important consideration for identifying sector-level substitution patterns, as the econometric results differed substantially (especially for beef) from the homogenous quality assumption. This will be an important consideration in any spatial equilibrium analyses of the agricultural economy.

The estimates of price elasticities for DDGS vis-à-vis other feed inputs represent best available evidence and are suitable for use in partial or economy-wide modeling frameworks aimed at richer development of the agricultural product and factor market impacts of changes in food and fuel demand. Notably, our results indicate that DDGS demands tend to be more responsive to price changes in energy-oriented feeds (as opposed to protein-oriented feeds), despite the historic feeding use of DDGS as a protein supplement in livestock diets. This has important implications for forward looking analysis of the agricultural economy in the biofuels era, as it is already the case that technological development in both ethanol and livestock feeding technology are focused on DDGS as a corn (energy) replacement in feed rations.

One possible limitation of this work is the use of the pseudo-data for the econometric analysis. The survey of work from Peeters and Surry (1997) concluded that the pseudo-data approach leads to larger elasticities than those produced by economic analysis using observed time-series data. Therefore, when time-series data becomes available regarding DDGS use it would be interesting to conduct a similar econometric analysis, and compare with these results.

It is worth noting that the maximum amount of biofuel likely to be produced from corn ethanol is around 15 billion gallons, and we are over 10 billion now.[8] The use of distiller's grains is beneficial to biofuel growth as this is an additional (the second largest) source of income (accounting of 10–20% of total income). If a large enough amount of ethanol is produced, then it is possible that the discount of distiller's grains to corn could limit biofuel growth. However, there is a strong market for DDGS and the price remains closely linked to the corn price, which has remained strong (albeit not at the recent record highs).

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[8]The potential growth is due to mandates (and economic incentives such as subsidies); however, corn-based ethanol is not economically competitive with gasoline at standard (i.e., less than $140/barrel) oil prices.

## REFERENCES

Augenstein, M.L., Johnston, L.J., Shurson, G.C., Hawton, J.D., & Pettigrew, J.E. (1997). Formulating farm-specific swine diets. Andover, MN: University of Minnesota Extension.

Binswanger, H.P. (1974). A cost function approach to the measurement of elasticities of factor demand and elasticities of substitution. American Journal of Agricultural Economics, 56(2), 377–386.

Bista, B., Hubbs, T., Richert, B.T., Tyner W.E., & Preckel, P.V. (2008, February). Economic value of ethanol co-products in swine diets: Evaluating profitability of corn fractionation techniques. Paper presented at Transition to a Bio-economy: Integration of Agricultural and Energy Systems, Atlanta, GA.

Clemens, R., & Babcock, B.A. (2008). Steady supplies or stockpiles? Demand for corn-based distillers grains by the U.S. beef industry (MATRIC Briefing Paper 08-MBP 14). Ames, IA: Iowa State University.

Fabiosa, J.F. (2008). Not All DDGS are created equal: Nutrient-profile-based pricing to incentivize quality (Working Paper 08-WP 481). Ames, IA: Iowa State University, Center for Agricultural and Rural Development.

Griffen, J.M. (1977). Long-run production modelling with pseudo-data: Electric power generation. Bell Journal of Economics, 8, 112–127.

Griffen, J.M. (1978). Joint production technology: The case of petrochemical. Econometrica, 46(2), 379–396.

Hertel, T.H., & McKinzie, L. (1986). Pseudo data as a teaching tool: Application to the translog, multiproduct profit function. Western Journal of Agricultural Economics, 11, 19–30.

Hertel, T.H., Tyner, W.E., & Birur, D.K. (2008). Biofuels for all? Understanding the global impacts of multinational mandates. West LaFayette, IN: Purdue University, Department of Agricultural Economics, Center for Global Trade Analysis.

Jones, C., Tonsor, G., Black, R., & Rust, S. (2007, April). Economically optimal distiller grain inclusion in beef feedlot rations: Recognition of omitted factors. Paper presented at NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management, Chicago, IL.

Keeney, R., & Hertel, T.W. (2005). GTAP-AGR: A framework for assessing the implications of multilateral changes in agricultural policies (GTAP Technical Paper No. 24). West LaFayette, IN: Purdue University, Center for Global Trade Analysis.

Klein, L.R. (1953). A textbook on econometrics. Evanston, IL: Row, Peterson.

Klopfenstein, T. (1996). Need for escape protein by grazing cattle. Animal Feed Science and Technology, 60(3), 191–199.

McKinzie, L., Paarlberg, P.L., & Huerta, I.P. (1986). Estimating a complete matrix of demand elasticities for feed components using pseudo data: A case study of Dutch compound feeds. European Review of Agricultural Economics, 13(1), 455–464.

Mergos, G.J., & Yotopoulos, P. (1988). Demand for feed inputs in the Greek livestock sector. European Review of Agricultural Economics, 15(1), 1–17.

National Resource Council. (1996). Nutrient requirements of swine. (10th ed. rev.). Washington, DC: National Academy Press.

National Resource Council. (2000). Nutrient requirements of beef cattle. Update 2000. (7th ed. rev.). Washington, DC: National Academy Press.

Peeters, L., & Surry, Y. (1997). A review of the arts of estimating price-responsiveness of feed demand in the European Union. Journal of Agricultural Economics, 48, 379–392.

Preckel, P., & Hertel, T.W. (1988). Approximating linear programs with summary functions: Pseudodata with an infinite sample. American Journal of Agricultural Economics, 70(2), 397–402.

Rae, R., & Strutt, A. (2005). Agricultural trade reform and nitrogen pollution in OECD countries (Agricultural Policy Discussion Paper No. 19). New Zealand Massey University.

Rude, J., & Meilke, K. (2000). Implications of CAP reform for the European Union's feed sector. Canadian Journal of Agricultural Economics, 48(4), 379–392.

St. Pierre, N.R., Threan, C.S., & Harvey, W.R. (1987). Minimum cost nutrient requirements from a growth response function. Journal of Animal Science, 64, 312–327.

Surry, Y. (1990). Econometric modelling of the European community compound feed sector: An application to France. Journal of Agricultural Economics, 41, 404–421.

Surry, Y., & Moschini, G. (1984). Input substitutability in the EC compound feed industry. European Review of Agricultural Economics, 11, 455–464.

Taheripour, F., Hertel, T.W., Tyner, W.E., Beckman, J.F., & Birur, D.K. (2008, July). Biofuels and their by-products: Global economic and environmental implications. Paper presented at the American Agricultural Economics Association Meeting, Orlando, FL.

Tokgoz, S., Elobeid, A., Fabiosa, J., Hayes, D., Babcock, B., Yu, T., et al. (2007). Emerging biofuels: Outlook of effects on U.S. grain, oilseed, and livestock markets (Staff Report 07-SR 101). Ames, IA: Iowa State University, Department of Economics.

Tyner, W.E. (2007). Policy alternatives for the future biofuels industry. Journal of Agricultural and Food Industrial Organization, 5(2), Article 2.

Tyner, W.E., & Taheripour, F. (2007). Renewable energy policy alternatives for the future. American Journal of Agricultural Economics, 89(5), 1303–1310.

University of Minnesota, Department of Animal Science. (2008). DDGS comparison tables. Retrieved August 4, 2008, from http://www.ddgs.umn.edu/profiles/us-profile%20comparison%20tables%20July%202008.pdf

Westcott, P.C. (2007). Ethanol expansion in the United States: How will the agricultural sector adjust? (FDS-07D-01). Washington, DC: United States Department of Agriculture.

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